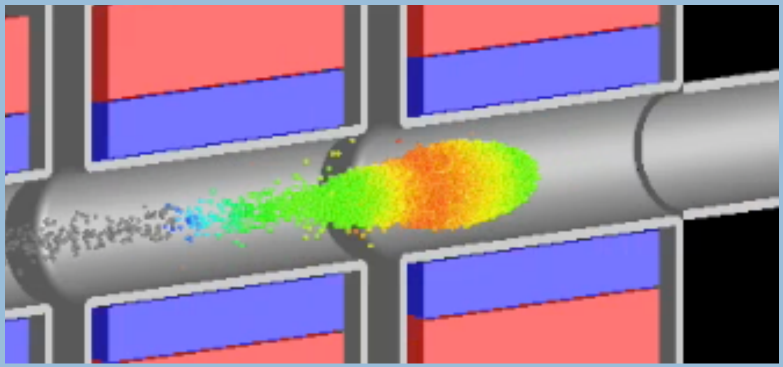
Beam Dynamics on NDCX-II*



Beam traversing an acceleration gap

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Ion Beam Driven High Energy Density Physics Workshop,
Pleasanton, CA, June 22-24, 2010

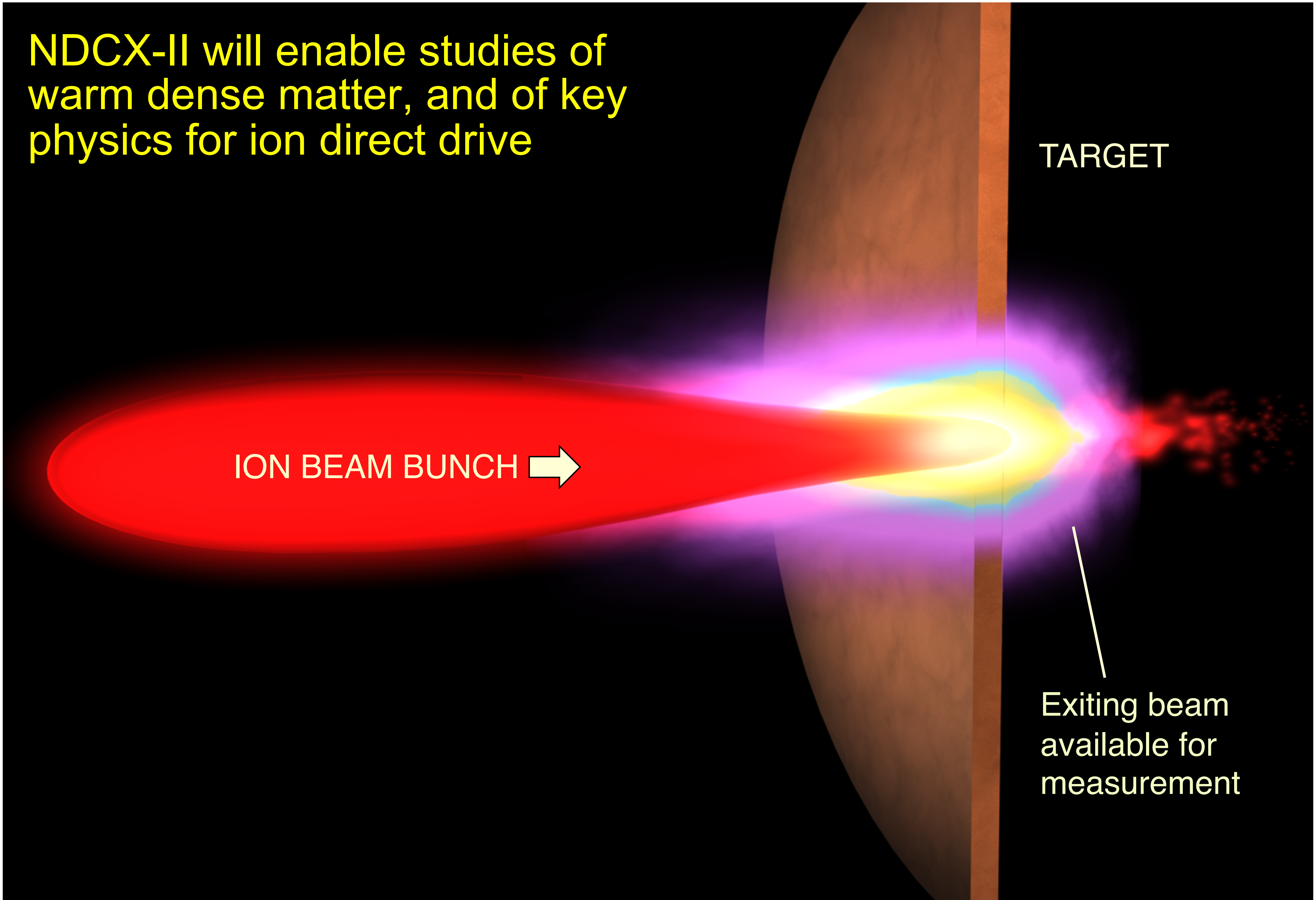
The Heavy Ion Fusion Science Virtual National Laboratory

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, by LBNL under Contract DE-AC02-05CH11231, and by PPPL under Contract DE-AC02-76CH03073.

Outline

- Introduction to the project
- 1-D ASP code model and physics design
- Warp (R,Z) simulations
- 3-D effects: misalignments & corkscrew
- Opportunities for beam dynamics studies

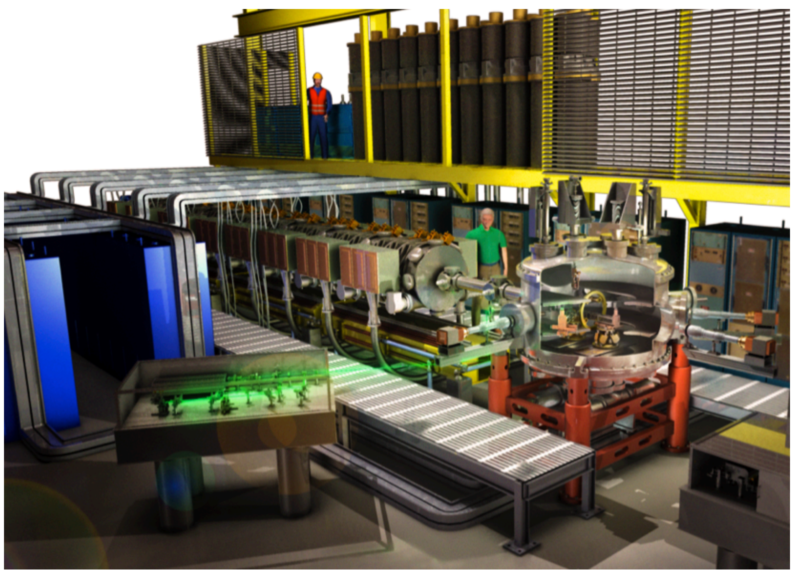
NDCX-II will enable studies of warm dense matter, and of key physics for ion direct drive



NDCX-II is underway at LBNL!

- DOE's Office of Fusion Energy Sciences approved the NDCX-II project earlier this year.

- $11 M of funding was provided via the American Recovery and Reinvestment Act ("stimulus package").

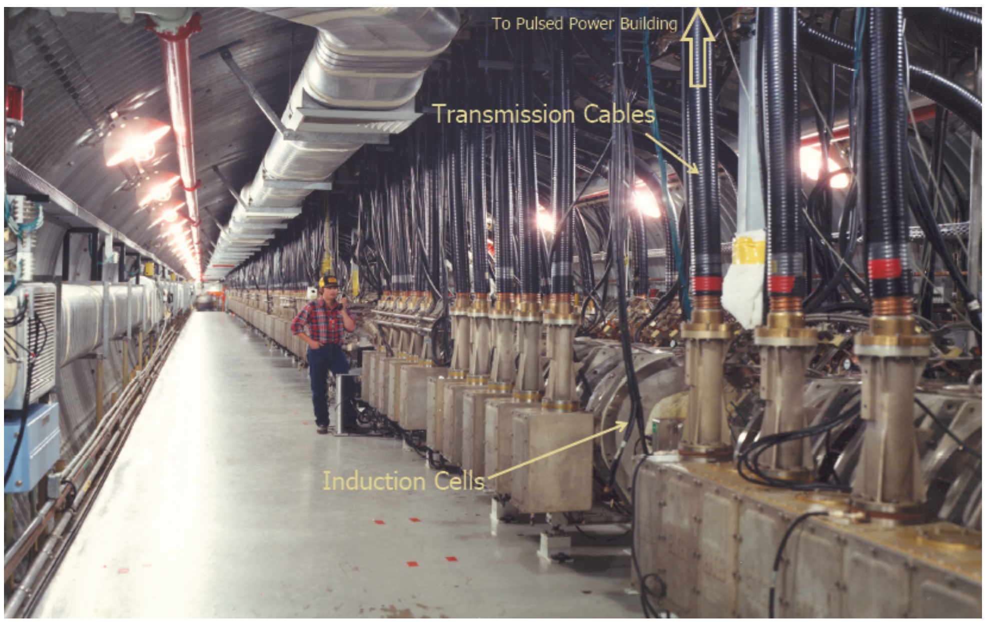


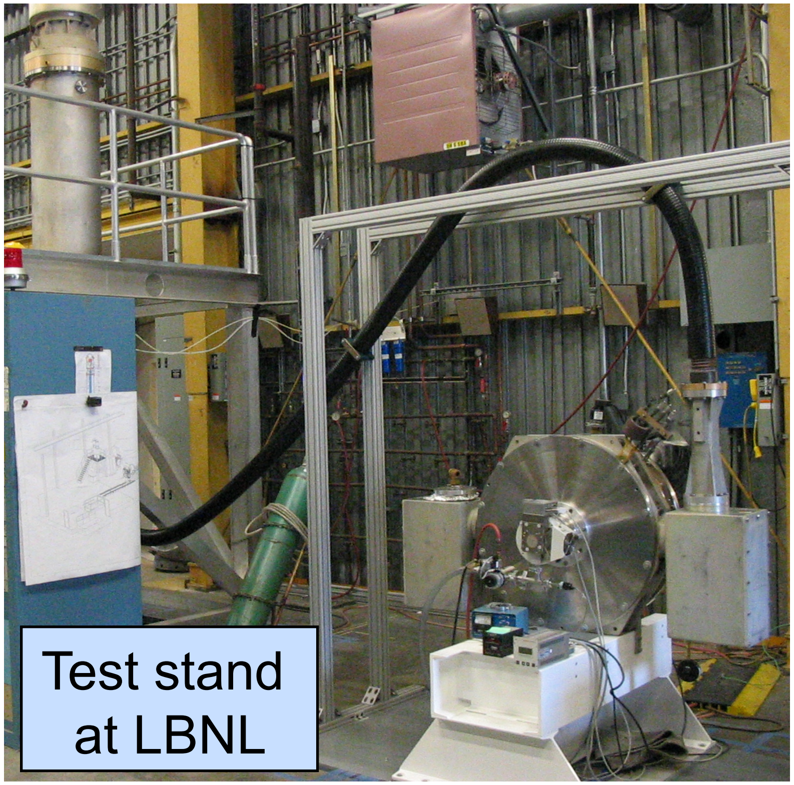
- Construction of the initial configuration with 15 +/- 3 cells began in July 2009, with completion planned for March 2012.
- Commissioning is to be in two 6-month phases.
- We hope to start target experiments in ~ October 2012, as we prepare for the second phase commissioning.

LLNL has given us 50 induction cells from the ATA electron accelerator

- Ferrite cores offer 1.4 x 10^{-3} Volt-seconds
- Blumlein voltage sources offer 200-250 kV with FWHM duration of 70 ns
- Longer beam at front end needs custom voltage sources < 100 kV
- Ion beam requires stronger (3T) pulsed solenoids and other cell modifications

Advanced Test Accelerator (ATA)

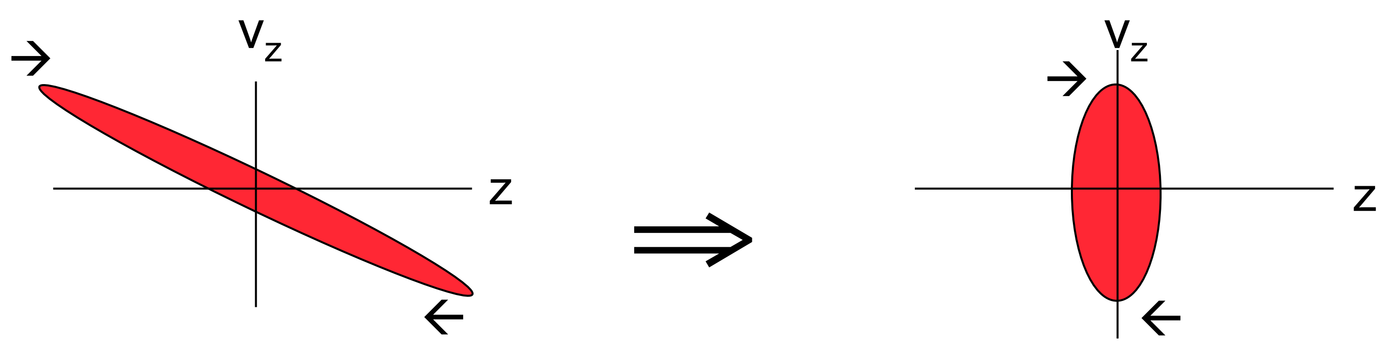




Test stand at LBNL

The “drift compression” process is used to shorten an ion bunch

- The process is analogous to “chirped pulse amplification” in lasers
- Induction cells impart a head-to-tail velocity gradient (“tilt”) to the beam
- The beam shortens as it moves down the beam line (pictures in beam frame):



Initial beam, with velocity tilt

compressed beam

- Space charge, if present, limits this compression
- To obtain a short pulse on target we introduce neutralizing plasma

NDCX-I at LBNL routinely achieves current and power amplifications exceeding 50x

injector

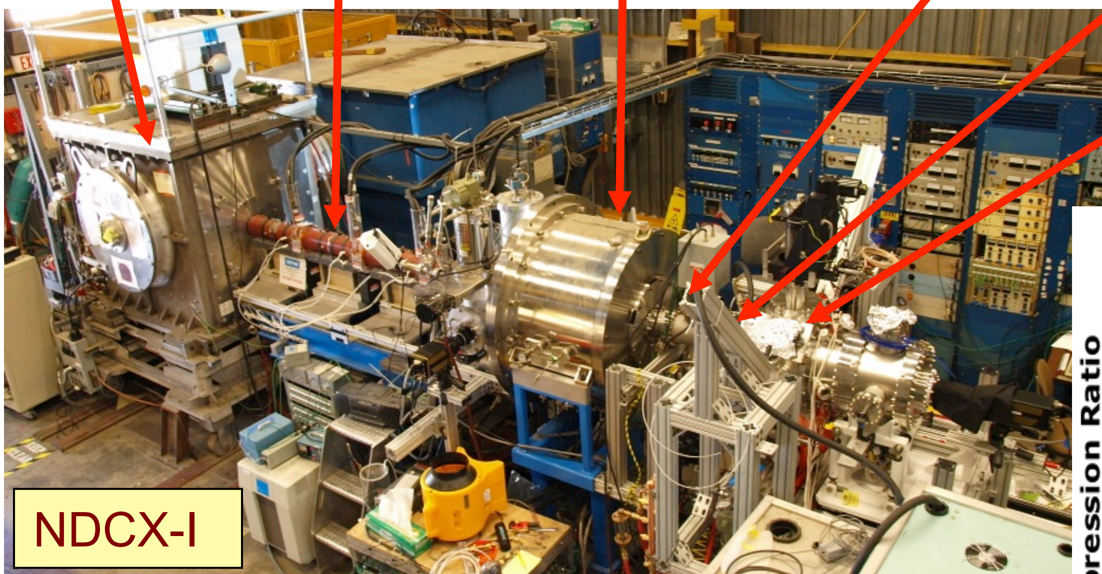
beam transport solenoids

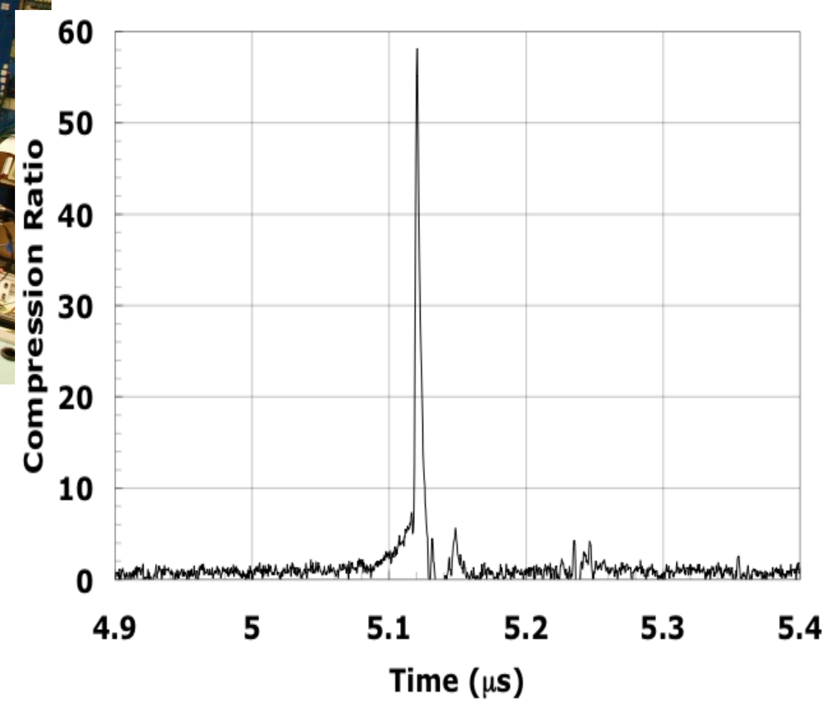
induction bunching module

drift compression line

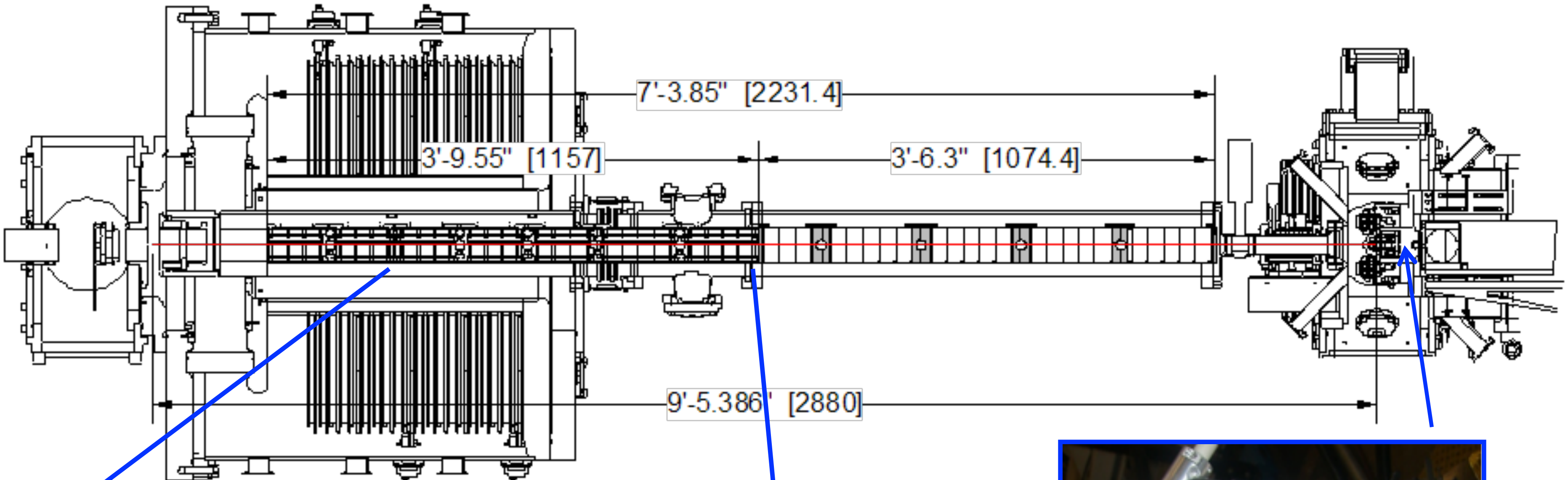
final focus solenoid

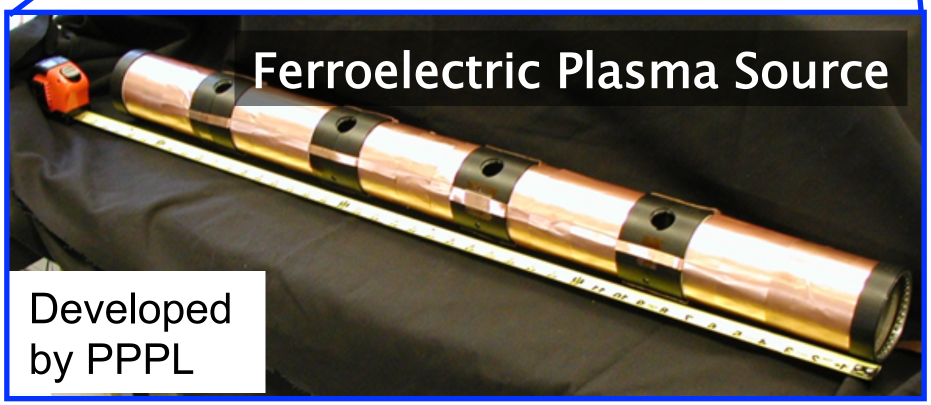
target chamber with plasma sources





NDCX-II beam neutralization is based on NDCX-I experience



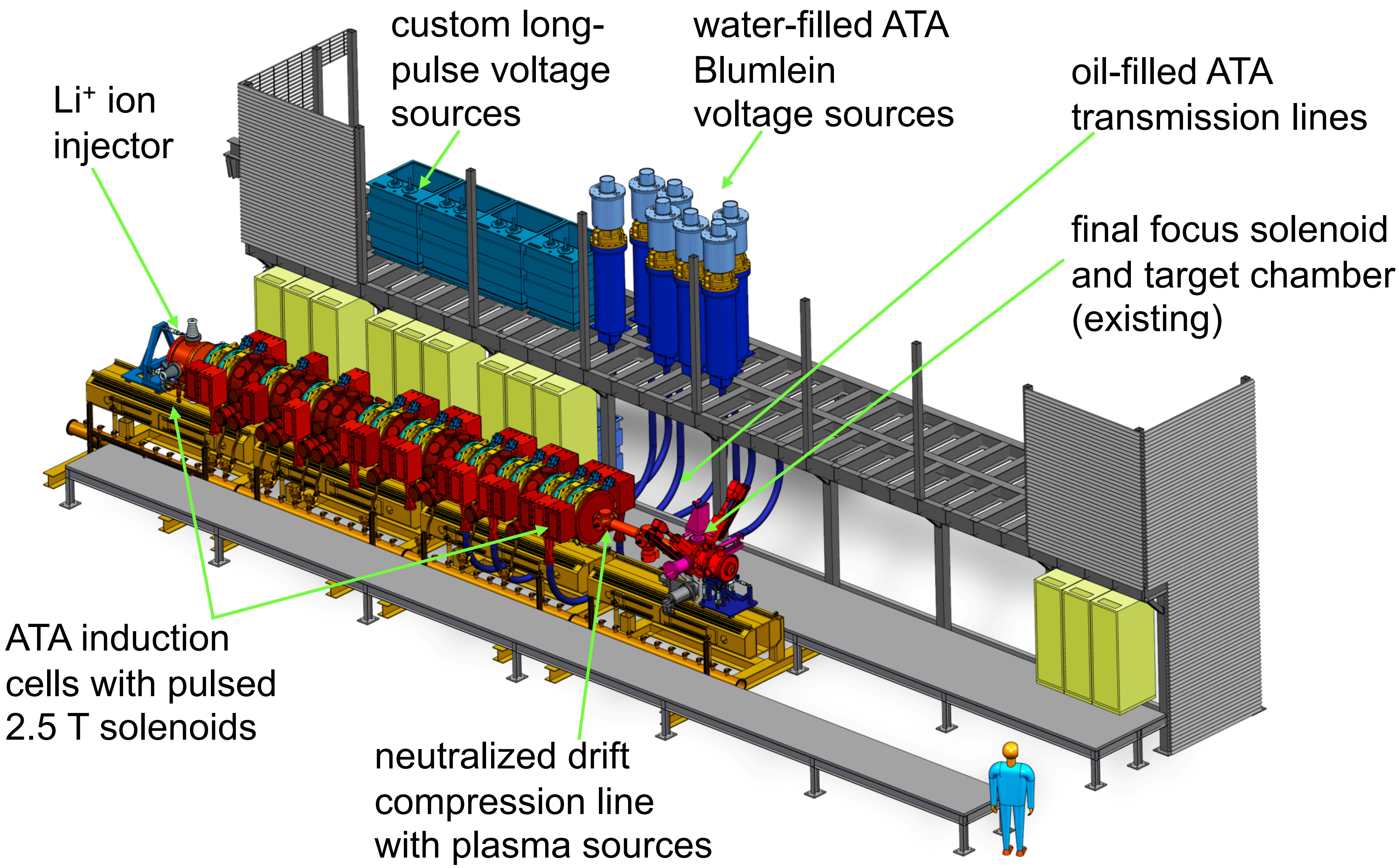


We employ the drift compression concept twice in NDCX-II

- Initial (non-neutralized) pre-bunching, to shorten the pulse duration for:
  - better use of induction-core Volt-seconds
  - early use of ATA Blumlein power supplies (~70 ns limit)

- Final "neutralized drift compression" onto the target
  - Electrons in plasma move to cancel the beam's electric field
  - Require $n_{plasma} > n_{beam}$ for this to work well

NDCX-II principal systems



The baseline employs 12 active induction cells; we will apply any unused contingency funds to expand the scope

	NDCX-I (bunched beam)	NDCX-II construction project			NDCX-II 21-cell (enhanced)
		12-cell (baseline)	15-cell ("probable")	18-cell ("possible")	
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Total charge	15 nC	50 nC	50 nC	50 nC	50 nC
Ion kinetic energy	0.3 MeV	1.2 MeV	1.7 MeV	2.4 MeV	3.1 MeV

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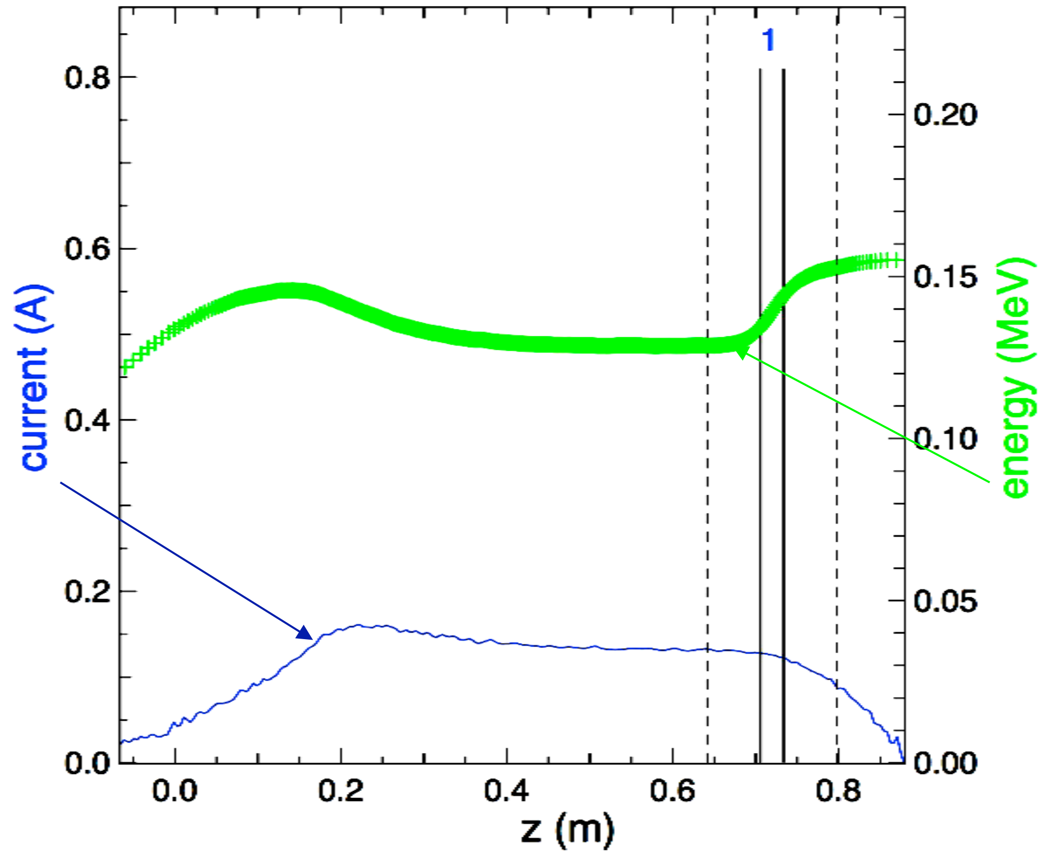
1-D simulation code ASP ("Acceleration Schedule Program")

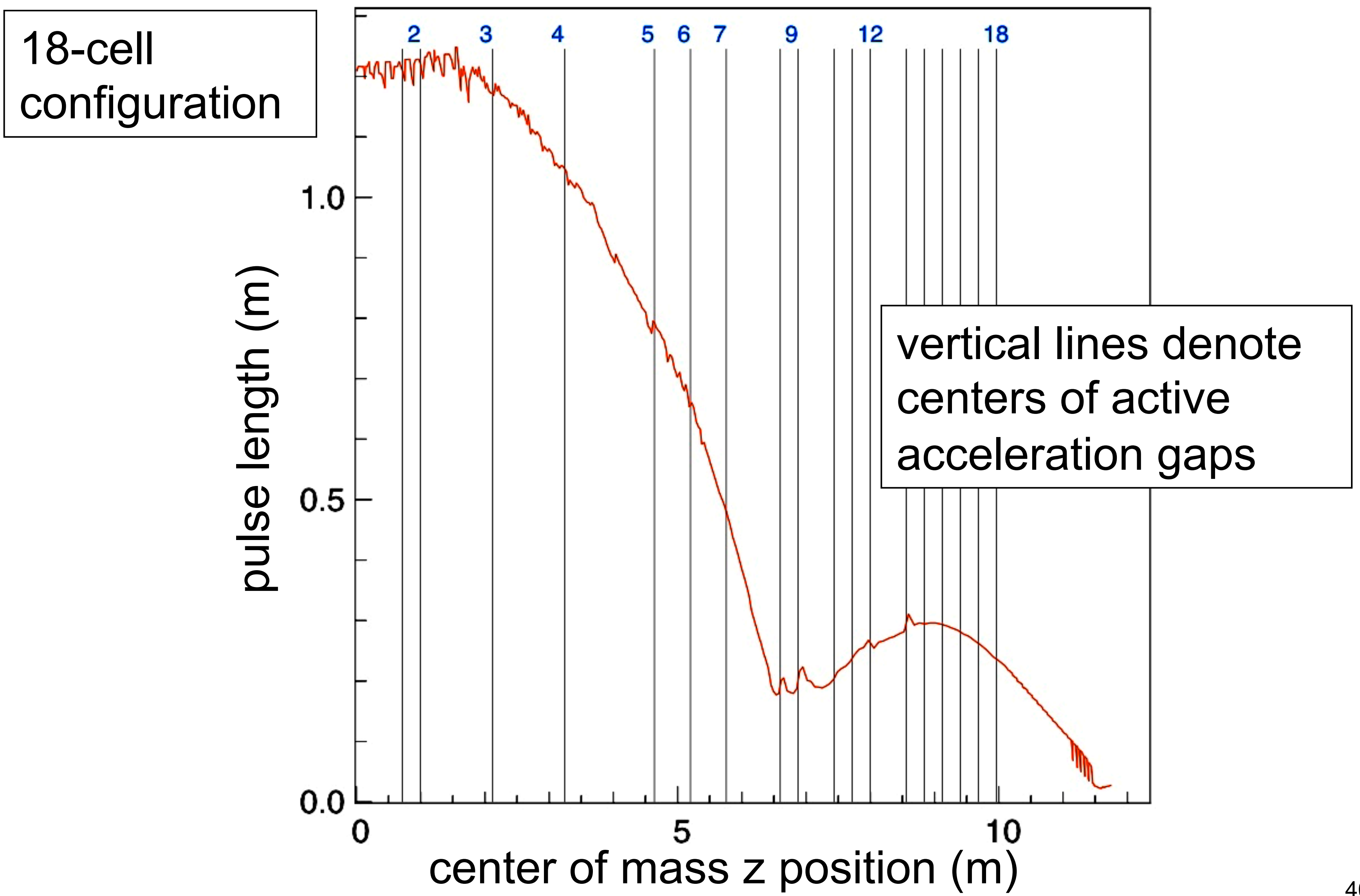
- Follows (z,v_z) phase space using a few hundred particles ("slices")

"Snapshots" of current and kinetic energy profiles vs. z, 120 ns into a simulated shot:



- Centroid tracking for studying imperfect alignment
- Optimization loops for waveforms & timings, dipole strengths (steering)
- Interactive (Python language with Fortran for intensive parts)

Pulse length vs. z, as developed using 1-D ASP simulation



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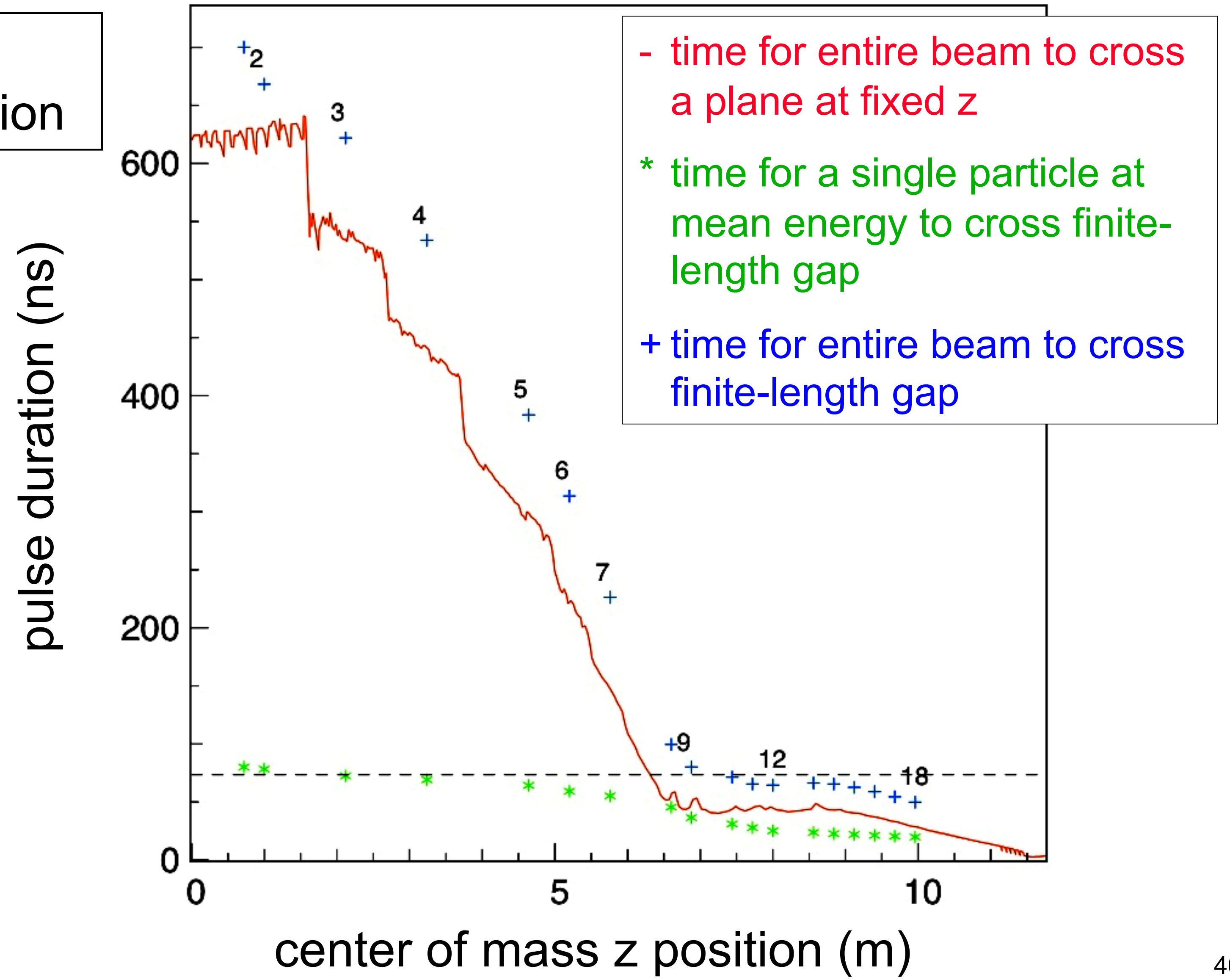
Pulse duration vs. z: the entire beam transit time is key

18-cell configuration



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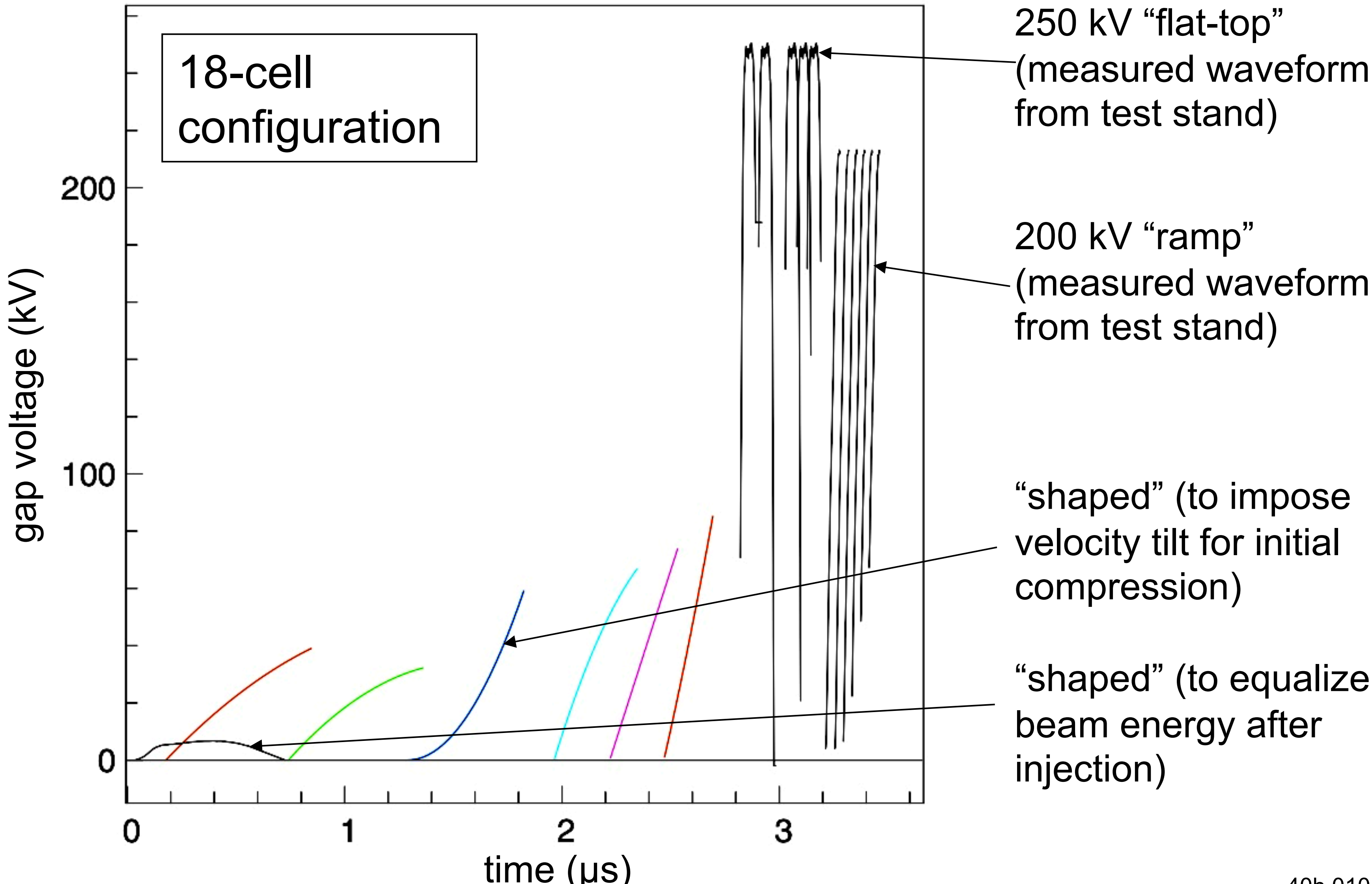
Voltage waveforms for all gaps



40h.010-18

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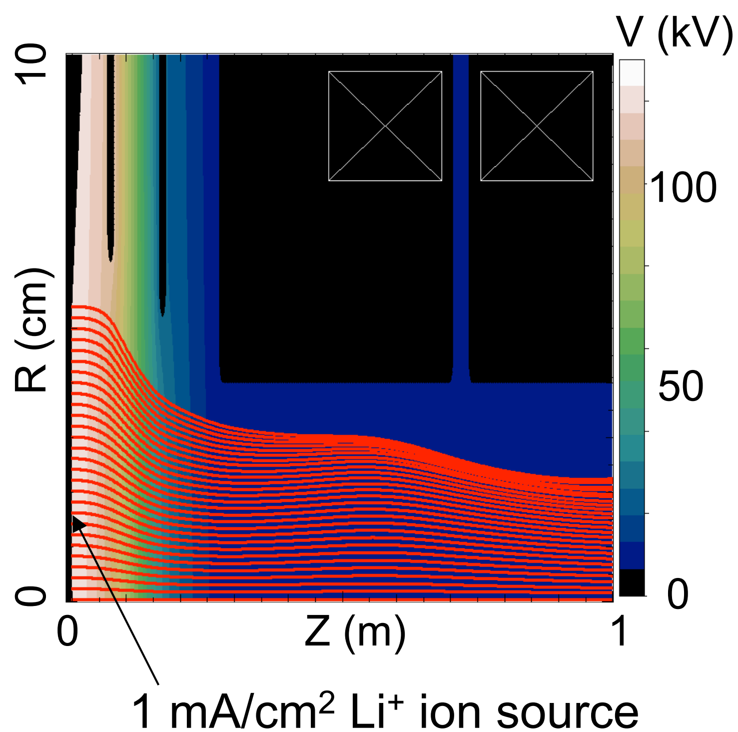
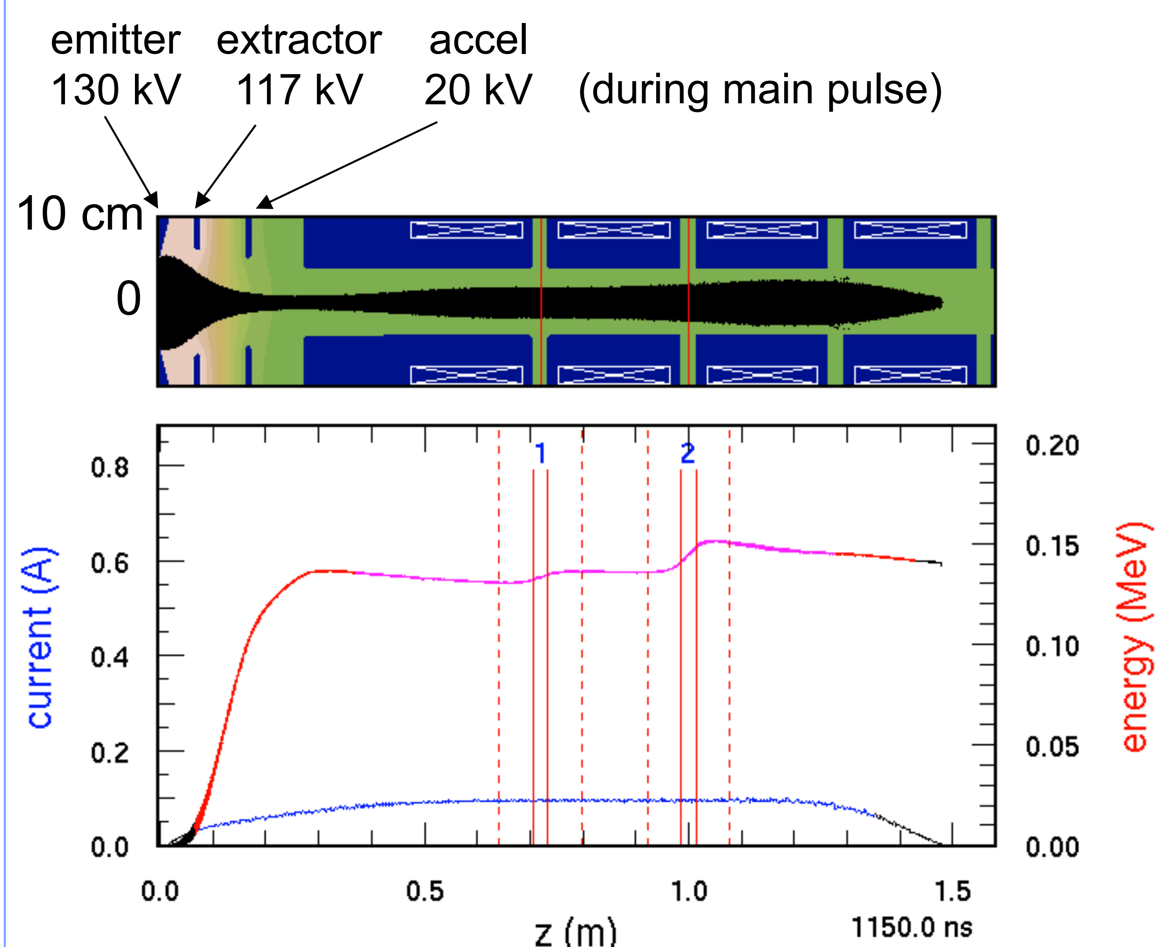
Injector design was developed using Warp in (r,z) geometry

First, used steady-flow "gun" mode to design for a nearly laminar flow:



Second, carried out fully time dependent simulation:



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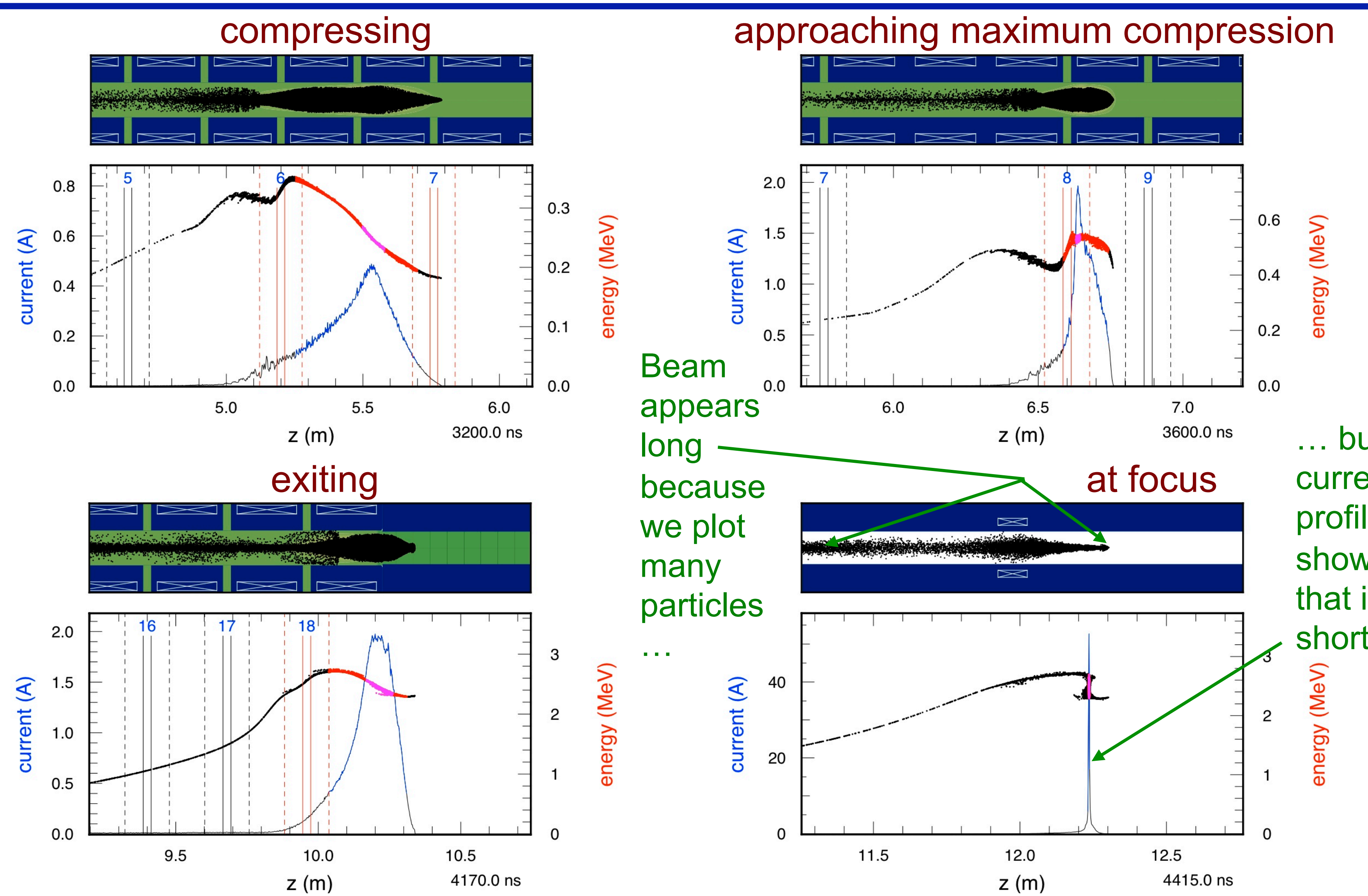
Snapshots from a Warp (r,z) simulation (18-cell version)

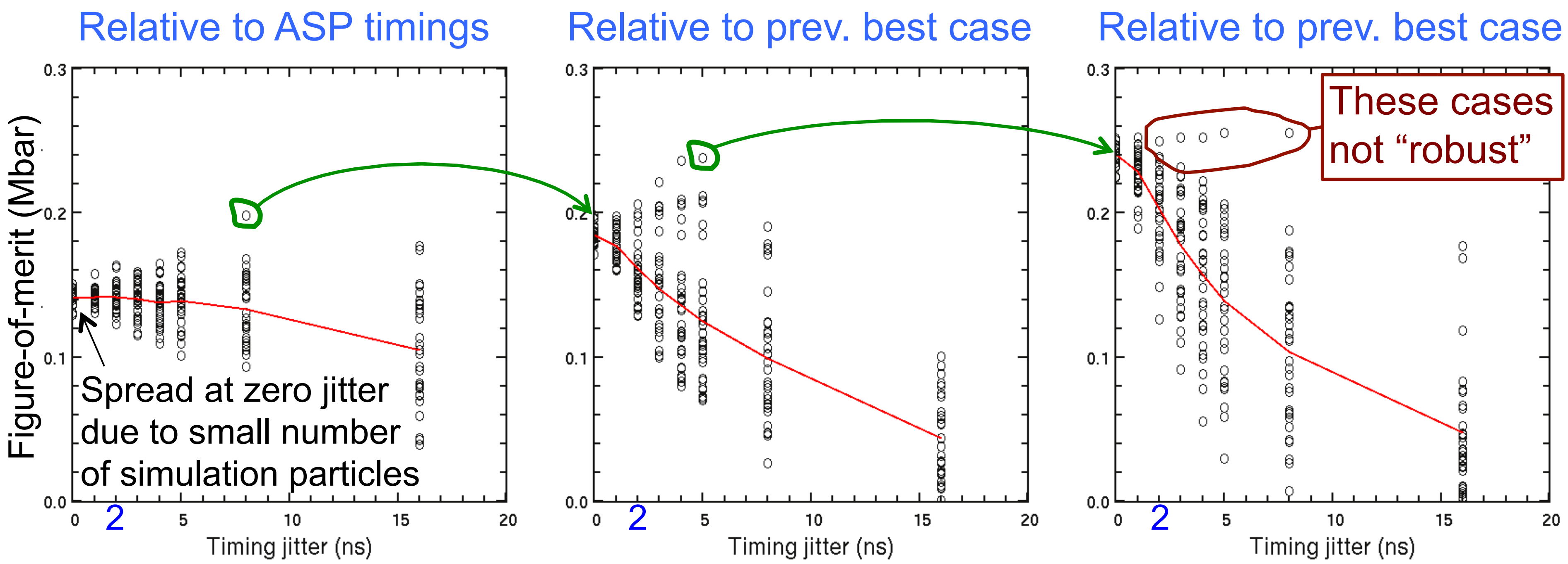


Beam appears long because we plot many particles …

… but current profile shows that it is short

40h-18

Ensembles of Warp (r,z) runs clarify effects of pulser timing jitter



- Random shifts within the assumed jitter were imposed on gap firing times; nominal NDCX-II spark-gap jitter is 2 ns
- Figure-of-merit is a rough estimate of max pressure (Mbar) in an Aluminum target
- Some perturbed cases worked better; we chose the best as the "new nominal"

(these results are for a configuration with 15 active ATA cells and an 8-T final focus solenoid)

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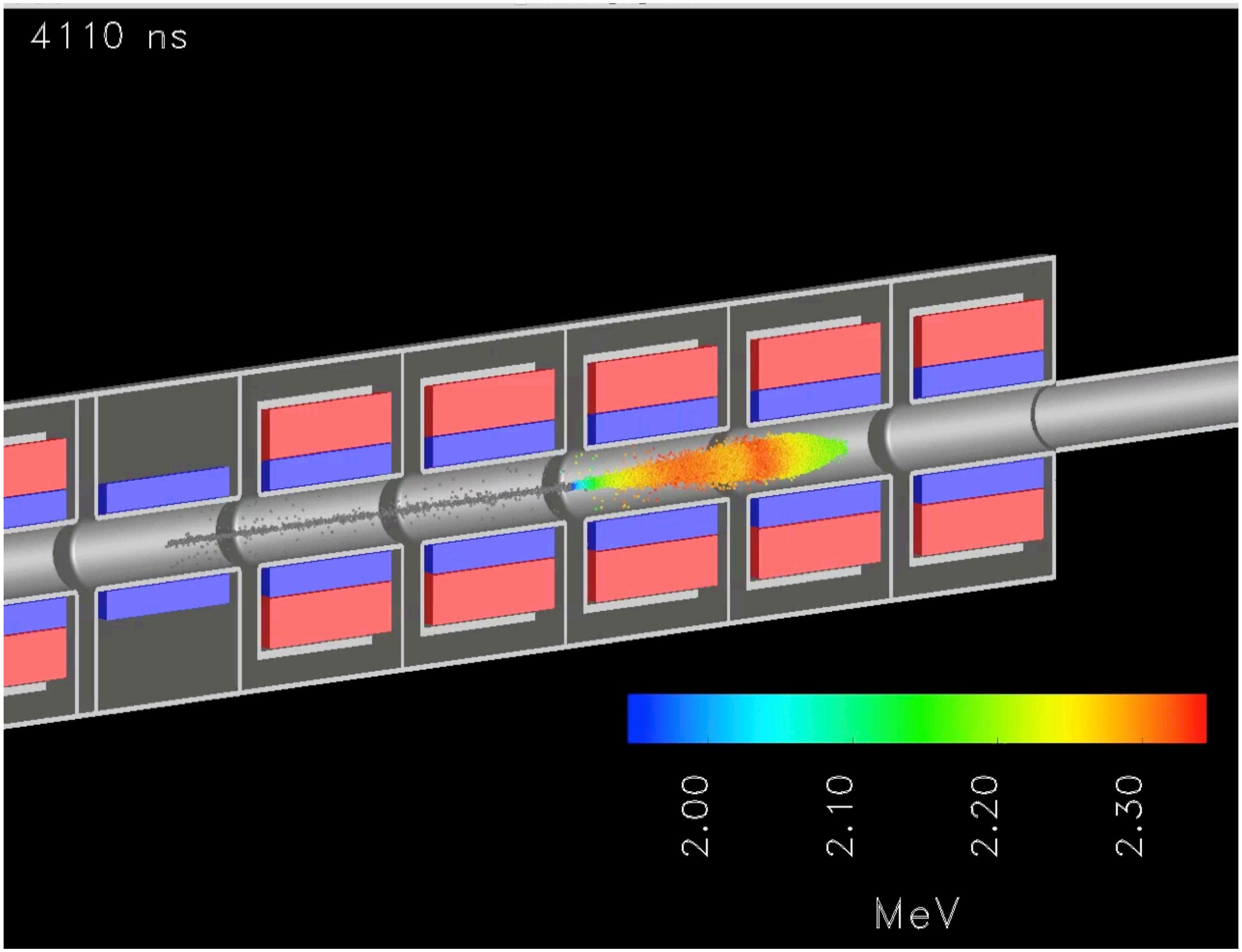
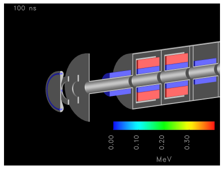
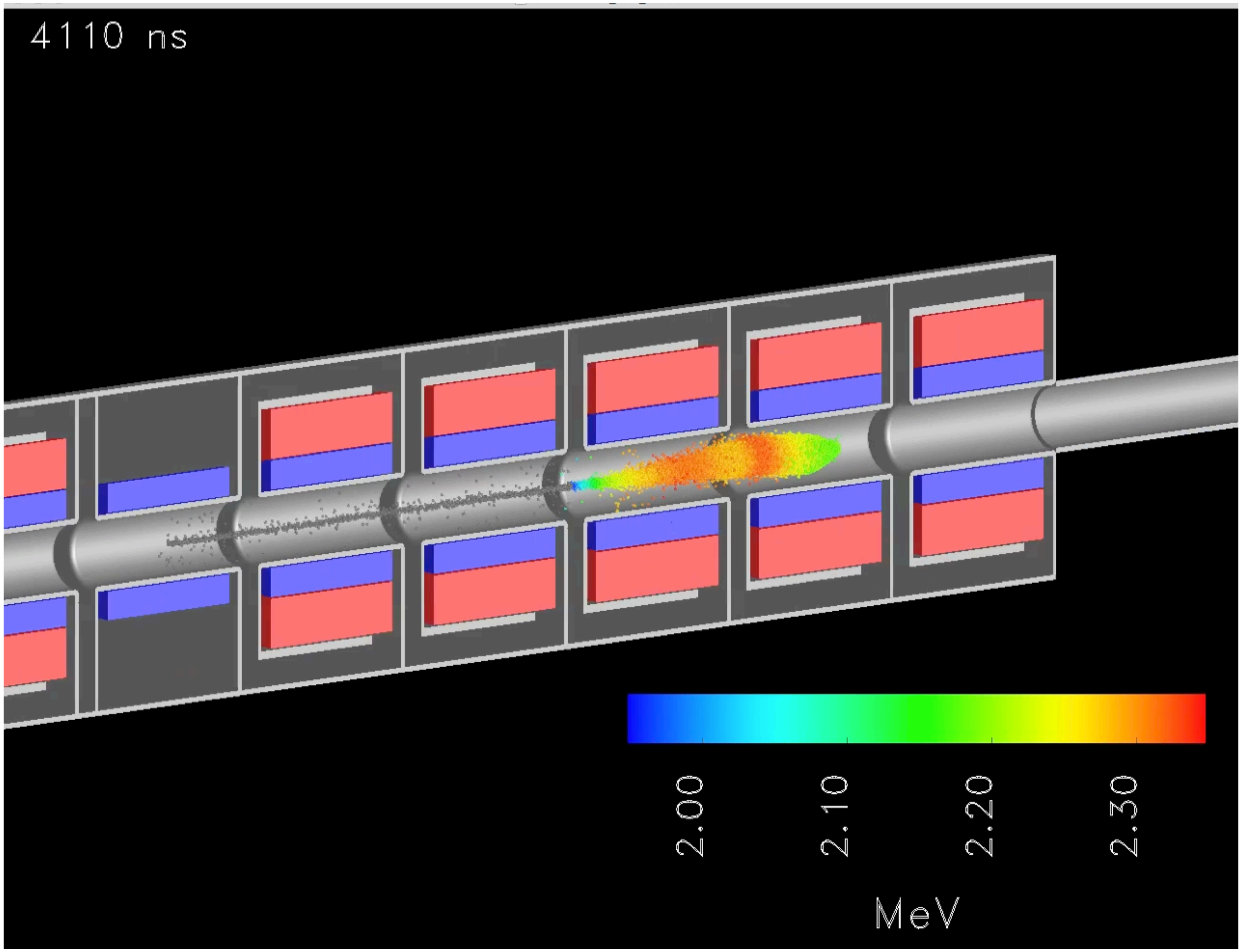
Video: Warp 3-D simulation of well-aligned 18-cell NDCX-II



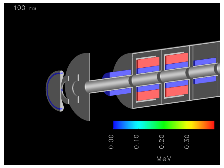
play video



Video: Warp 3D simulation of 18-cell NDCX-II, including random offsets of solenoid ends by up to 2 mm (0.5 mm is nominal)

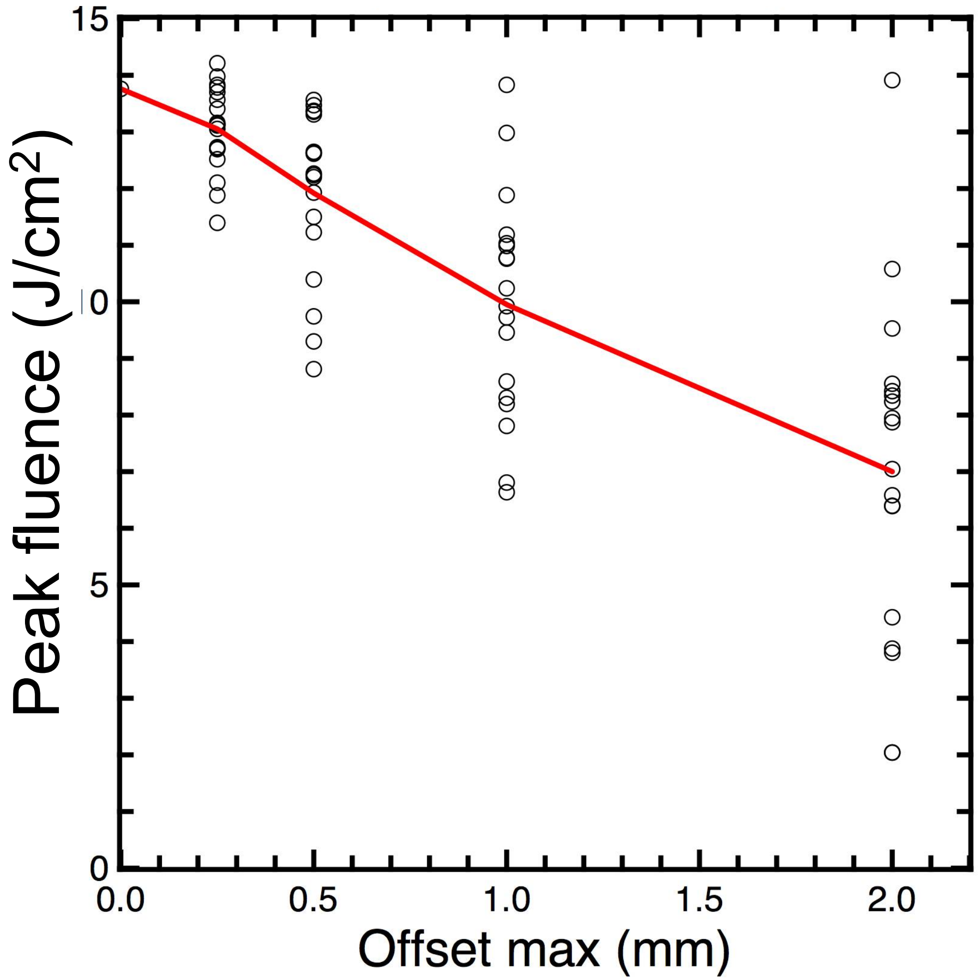


play video



Warp 3D simulations indicate slow degradation of the focus as misalignment of the solenoids increases (without steering)

- Random offsets in x and y were imparted to the solenoid ends.
- The offsets were chosen from a uniform distribution with a set maximum.

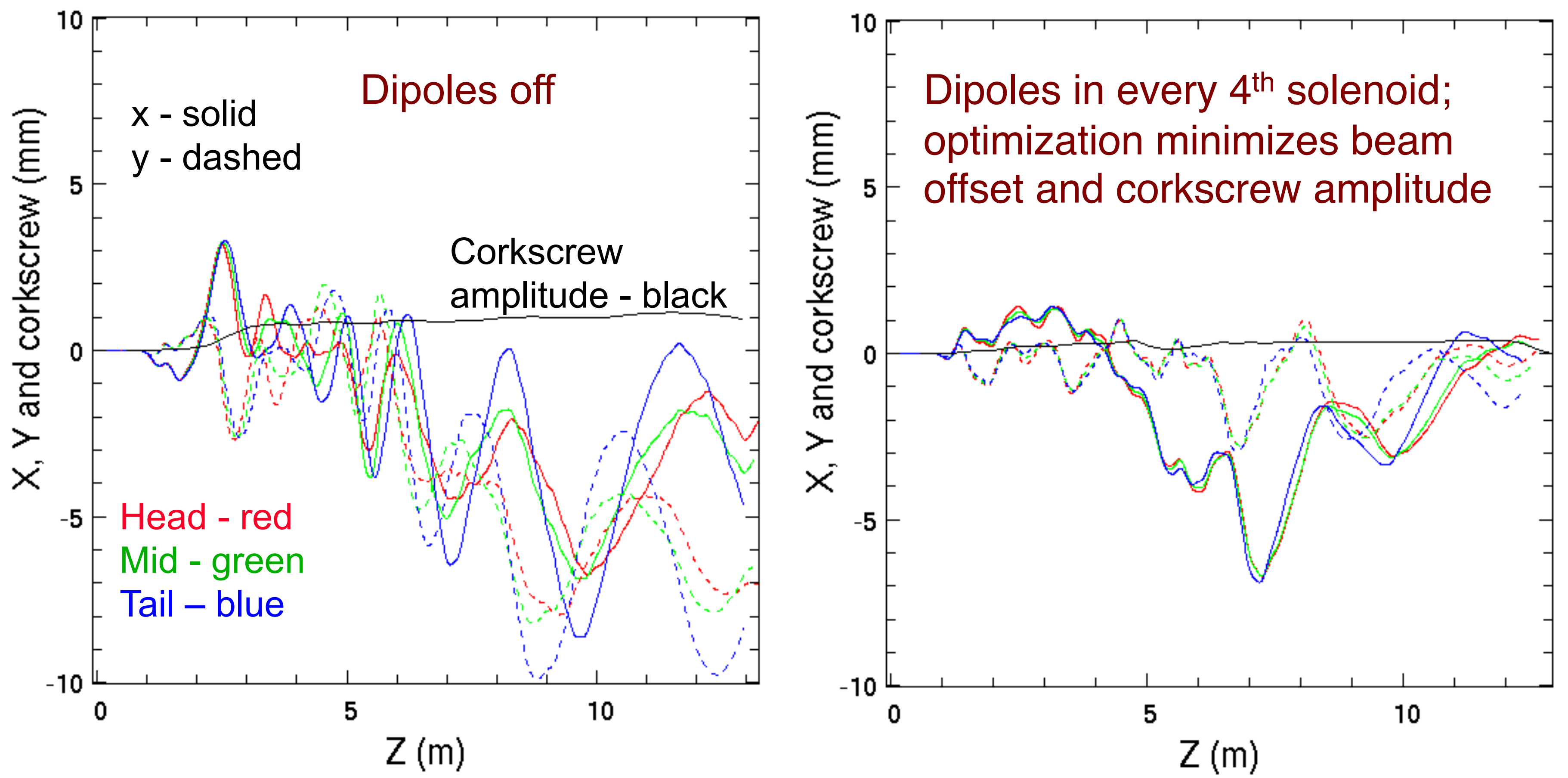


(This series used an older 15-cell design based on a 2 mA/cm^2 source)

35g-15

To assess steering, we again used the fast ASP code; a tuning algorithm (as in ETA-II, DARHT)‡ adjusts dipole strengths

Trajectories of head, mid, tail particles, and corkscrew amplitude, for a 34-cell ASP run. Random offsets of solenoid ends up to 1 mm were assumed; the effect is linear.



‡ Y-J. Chen, Nucl. Instr. and Meth. A **398**, 139 (1997).

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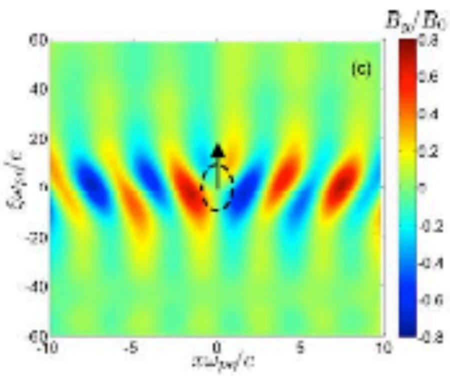
NDCX-II will be an exciting platform for beam physics studies (many of them relevant to an HIF driver)

- NDCX-II operation embodies collective beam dynamics:
  - Driver-like compression of non-neutral and neutralized beams
  - Space charge-driven removal of velocity tilt, to achieve “stagnation”
  - Longitudinal waves are evident
- Non-ideal effects include:
  - Emittance growth (phase-space dilution), “halo” formation
  - Beam - plasma interactions and instabilities
  - Aberrations in final focus
- Add-on hardware could enable studies of:
  - Collective focusing of ion beams
  - Intense beam transport in quadrupoles
  - Beam dynamics in bends
- Beam diagnostics will be developed and improved

NDCX-II will enable greater understanding of beams in plasmas

Electromagnetic fields are excited by a moving beam in a magnetized plasma:

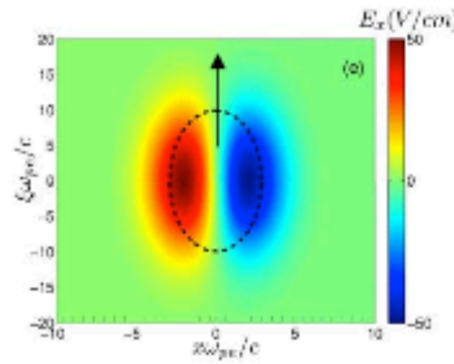
Wave field (can extend far outside the bunch)



Can be used for diagnostics

M. Dorf, I. Kaganovich, E. Startsev, and R. C. Davidson, Phys. Plasmas **17**, 023103 (2010).

Local field (falls off rapidly outside the bunch)



Can provide bunch focusing

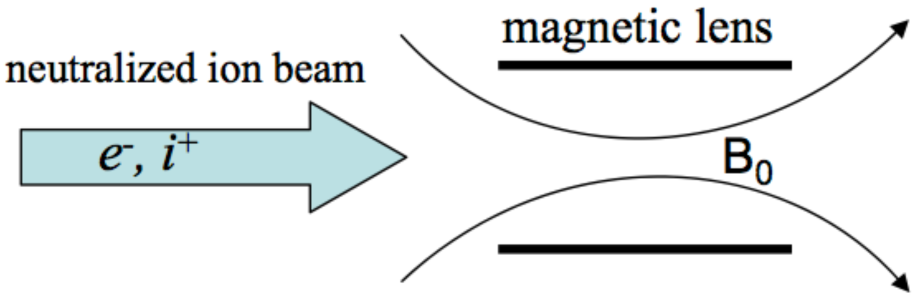
M. Dorf, I. Kaganovich, E. Startsev, and R. C. Davidson, PRL **103**, 075003 (2009)

(This material -- thanks: M. Dorf)

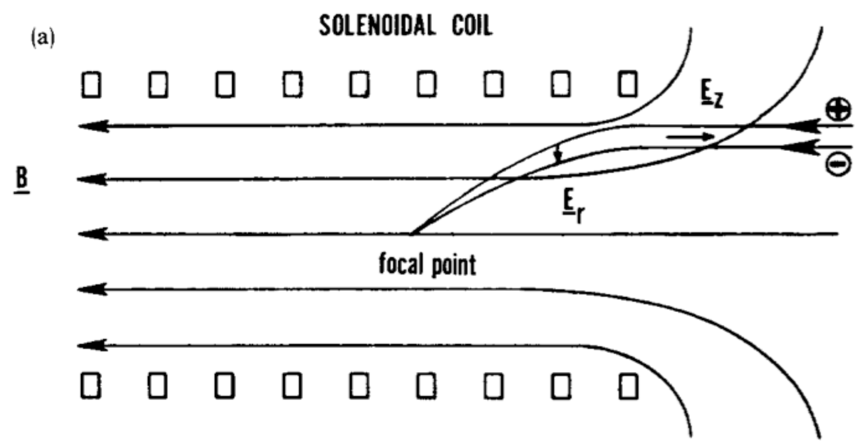
Review paper: I. D. Kaganovich, *et al.*, Phys. Plasmas **17**, 056703 (2010)

The “Robertson lens” offers collective focusing in a quasi-neutral system

- An ambipolar electrostatic field brings both species to a common focus
- For a given focal length, the required B_0 is smaller by a factor of $(m_e/m_i)^{1/2}$



Neutralizing electrons come from outside the magnetic field; no plasma inside the solenoid



(from Kraft paper)

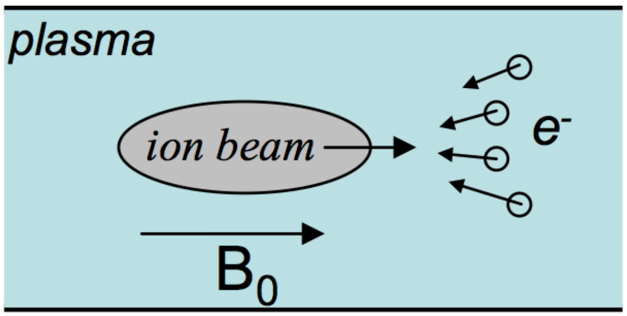
Focusing force on beam: $F_r = -\frac{r}{4} m_i \Omega_e \Omega_i \quad (\Omega_i = Z_b e B_0 / m_i c)$

References: S. Robertson, *Phys. Rev. Lett.* **48**, 149 (1982).
R. Kraft, B. Kusse, & J. Moschella, *Phys. Fluids* **30**, 245 (1987).

requires:
$r_b << c/\omega_{pe}$
$\omega_{pe} >> \omega_{ce}$

Beam self-focusing force is greatly enhanced, relative to magnetic self-pinching, by a weak solenoid B field (~100 G)

The enhanced focusing is provided by a strong radial electric field that arises due to a local polarization of the magnetized plasma background by the moving ion beam.

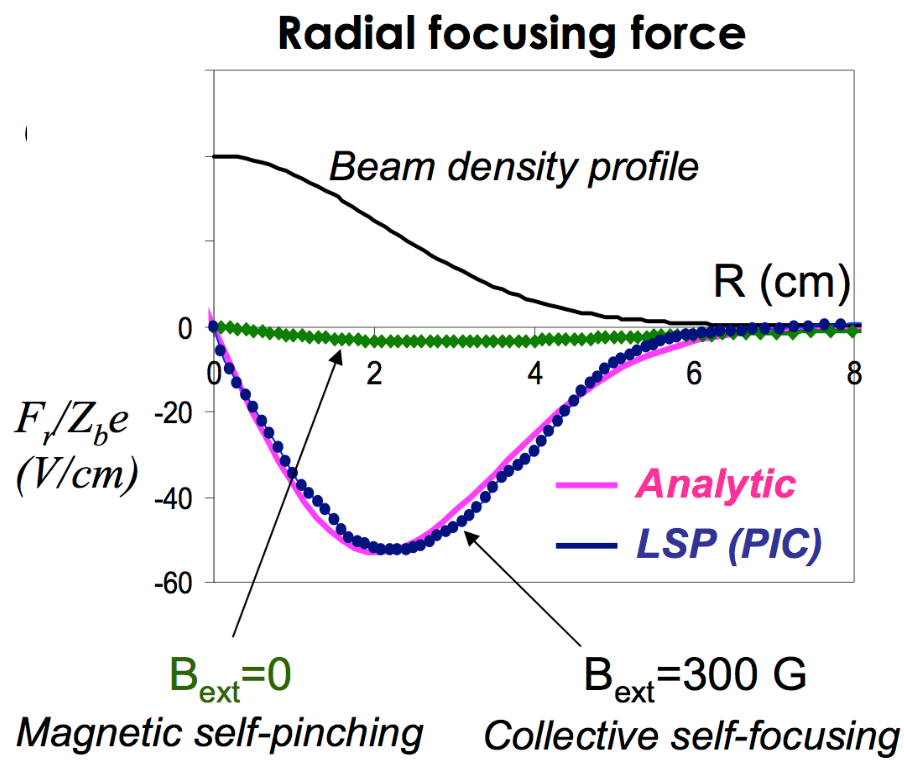


Provided the beam current is neutralized, *i.e.*, $Z_b n_b v_b = n_e v_{ez}$:

$$F_r = Z_b^2 m_e v_b^2 \frac{1}{n_e} \frac{dn_b}{dr}$$

Relative focusing strengths:
NDCX-I: $F_r L_{drift} / F_{sol} L_{sol} \sim 0.04$
NDCX-II: $F_r L_{drift} / F_{sol} L_{sol} \sim 0.5$

M. Dorf, et al., PRL 103, 075003 (2009)



requires:

$r_{ge} << r_b << c/\omega_{pe}$ $\quad r_{ge} \equiv \frac{v_b}{\omega_{ce}}\left(1+\frac{\omega_{ce}^2}{\omega_{pe}^2}\right)^{1/2}$

$\Rightarrow \omega_{ce} >> 2\beta_b \omega_{pe}$

Things we need to measure, and the diagnostics we'll use

Non-intercepting (in multiple locations):

- Accelerating voltages: voltage dividers on cells
- Beam transverse position: four-quadrant electrostatic capacitive probes
- Beam line charge density: capacitive probes
- Beam mean kinetic energy: time-of-flight to capacitive probes

Intercepting (in two special "inter-cell" sections):

- Beam current: Faraday cup
- Beam emittance: two-slit or slit-scintillator scanner
- Beam profile: scintillator-based optical imaging
- Beam kinetic energy profile: time-of-flight to Faraday cup
- Beam energy distribution: electrostatic energy analyzer

(Underlined items will be available at commissioning)

NDCX-II potential performance for “well tuned” configurations

	NDCX-I (bunched beam)	NDCX-II construction project			NDCX-II 21-cell (enhanced)
		12-cell (baseline)	15-cell (“probable”)	18-cell (“possible”)	
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Total charge	15 nC	50 nC	50 nC	50 nC	50 nC
Ion kinetic energy	0.3 MeV	1.2 MeV	1.7 MeV	2.4 MeV	3.1 MeV
Focal radius (50% of beam)	2 mm	0.6 mm	0.6 mm	0.6 mm	0.7 mm
Duration (bi-parabolic measure = √2 FWHM)	2.8 ns	0.9 ns	0.4 ns	0.3 ns	0.4 ns
Peak current	3 A	36 A	73 A	93 A	86 A
Peak fluence (time integrated)	0.03 J/cm^2	13 J/cm^2	19 J/cm^2	14 J/cm^2	22 J/cm^2
Fluence w/in 0.1 mm diameter, w/in duration		8 J/cm^2	11 J/cm^2	10 J/cm^2	17 J/cm^2
Max. central pressure in Al target		0.07 Mbar	0.18 Mbar	0.17 Mbar	0.23 Mbar
Max. central pressure in Au target		0.18 Mbar	0.48 Mbar	0.48 Mbar	0.64 Mbar

Caveats: these are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm^2 emission, front-end pulses that match the design, and perfect neutralization; they use only measured Blumlein waveforms

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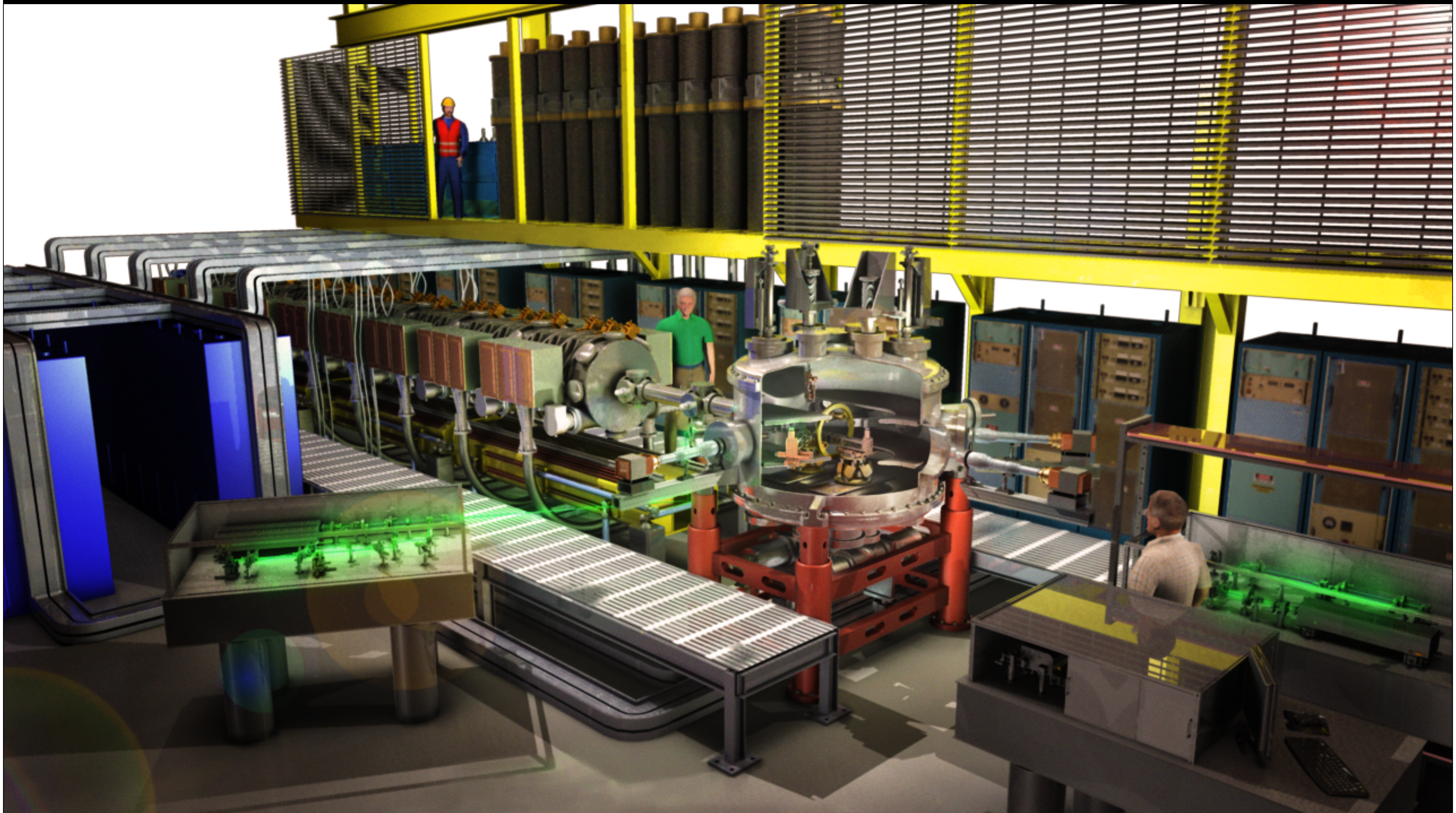

NDCX-II Warm Dense Matter Research Facility

We look forward to a novel and flexible research platform

- NDCX-II will be a unique ion-driven user facility for warm dense matter and IFE target physics studies.
- The machine will enable a multiplicity of beam dynamics experiments, of both inherent interest and relevance to high-current fusion drivers.